

---

# Black River Pump Station Juvenile Salmon Downstream Fish Passage Study

---



November 2020



**King County**

Department of Natural Resources and Parks  
Water and Land Resources Division

**Science and Technical Support Section**

King Street Center, KSC-NR-0704  
201 South Jackson Street, Suite 704  
Seattle, WA 98104

206-477-4800 TTY Relay: 711  
[www.kingcounty.gov/EnvironmentalScience](http://www.kingcounty.gov/EnvironmentalScience)

Alternate Formats Available  
206-477-4800 TTY Relay: 711

---

---

---

---

# **Black River Pump Station Juvenile Salmon Downstream Passage Study**

## **Prepared for:**

Tom Bean, Special Projects Engineer  
King County Water and Land Resources Division  
Department of Natural Resources and Parks

## **Submitted by:**

Chris Gregersen  
King County Water and Land Resources Division  
Department of Natural Resources and Parks



**King County**

Department of  
Natural Resources and Parks  
**Water and Land Resources Division**

---

---

---

## **Acknowledgements**

---

The author would like to thank the River and Floodplain Management Section and King County Flood Control District for funding this study. Also, special thanks to Washington Department of Fish and Wildlife (WDFW) for providing juvenile salmon for use in this study, West Fork Environmental for providing installation of tracking technology, and the Wastewater Treatment Division Operations team that runs the Black River Pump Station for continued assistance throughout the study.

*Cover photo courtesy of King County River and Floodplain Management Section*

## **Citation**

---

King County. 2020. Black River Pump Station Juvenile Salmon Downstream Passage Study. Prepared by Chris Gregersen, Water and Land Resources Division. Seattle, Washington.

# Table of Contents

---

Executive Summary .....	iv
1.0 Introduction .....	1
2.0 Methods.....	6
2.1 PIT System .....	6
2.2 PIT Tagging Process.....	7
2.3 Releasing Study Fish.....	8
2.4 Detection Efficiency Testing.....	9
2.5 Tag Retention and Mortality .....	11
3.0 results .....	12
3.1 PIT Antenna Detection Efficiency .....	12
3.2 Overall Passage Efficiency.....	13
3.3 Passage Timing .....	14
3.4 Diel Movement of Fish through BRPS.....	16
3.5 Downstream Fish Counting Vault Blockage .....	17
4.0 Discussion and conclusions.....	20
4.1 Caveats.....	23
5.0 Recommendations.....	24
5.1 Near-term Actions .....	24
5.2 Implications for Fish Passage Facility Design.....	24
5.3 Future Monitoring Recommendations .....	25
6.0 References.....	27

## Figures

---

Figure 1. BRPS diagrams adapted from Jacobs (2020).....	2
Figure 2. Diagram of BRPS airlift high and low fish ports, conveyance pipes, and airlift de-aeration tank. ....	3
Figure 3. PIT tag reader and antenna located at the downstream counting vault. ....	7
Figure 4. Release Locations for PIT tagged coho and Chinook.....	9
Figure 5. Counting vault condition during blockage before (left), and after 4/1 with counting ports and screen removed (right).....	10

Figure 6.	Actual tag detection times for all tagged Chinook detected successfully passing the BRPS downstream facility. ....	15
Figure 7.	Actual tag detection times for all tagged coho detected successfully passing the BRPS downstream facility. ....	16
Figure 8.	Diel detections of juvenile Chinook and coho detected moving through the BRPS downstream facility. ....	17
Figure 9.	Deceased coho observed during the counting vault blockage, including two PIT tagged hatchery fish (top and middle), and one wild fish (bottom). ....	19
Figure 10.	Wild steelhead smolt observed during the counting vault blockage. ....	19

## **Tables**

---

Table 1.	Detection efficiency tests conducted during the study. ....	13
Table 2.	Overall passage efficiency calculations for all Chinook and coho released upstream of BRPS. ....	14

## **EXECUTIVE SUMMARY**

---

The Black River Pump Station (BRPS) is a flood control facility located in Renton, WA. The purpose of this facility is to provide flood risk reduction to areas of Renton, Kent, and Tukwila—protecting over 2,800 acres and an estimated \$4.4 billion in assessed value. The current BRPS features both adult upstream and juvenile downstream passage, which were built in 1971, and have operated continuously since 1972. The downstream fish passage facility is different from passive passage facilities in that it actively transports fish from the Black River forebay to the tidally influenced tailrace which frequently has a higher water elevation. This is accomplished using an airlift system, which provides fish passage by injecting air into vertical pipes, thereby creating lift and carrying water and fish upwards and out to the Green River. Passage is provided by water drawn through a series of 5.25-inch square ports located on the intake pier walls within the forebay.

The BRPS began operation in 1972, prior to the Endangered Species Act listings of Puget Sound Chinook and Puget Sound steelhead. In order to pass upstream and downstream migrating fish around the structure, unique fish passage systems were constructed and continue to be in operation. However, the existing fish passage and exclusion systems do not meet current federal fish passage design requirements for upstream or downstream fish passage and are believed to hinder migration and harm fish (Jacobs 2020). After almost 50 years of continual operation, the pump station needs to be rehabilitated to meet current standards and ensure safe, reliable, and efficient operations. Planning, designing, and implementing upgrades began in 2018 and will occur over 7–10 years in distinct phases. TetraTech (2015) recommended testing the current downstream passage facilities as an initial measure needed to understand what parts of the system functioned well and what parts might need to be improved. This includes evaluating the performance of the current system and measuring migration through the facility using a fish tag and recapture protocol.

The purpose of this study is to better understand the overall effectiveness of the existing downstream passage facility by utilizing live fish, which were tagged, released upstream, and tracked through the facility. This was accomplished by utilizing juvenile coho and Chinook salmon obtained from the WDFW Soos Creek hatchery, which were then fitted with PIT (Passive Integrated Transponder) tags and released at two locations upstream of the BRPS facility. Overall passage efficiency was assessed by installing a PIT tag antenna within the downstream facility to document the passage of tagged Chinook and coho as they migrated downstream through the system.

Results of this study suggest that downstream passage efficiency at BRPS is far below the federal requirement of 75% recently required for the Howard Hanson Dam (HHD) downstream passage facility. While HHD has much more area and higher quality upstream salmonid habitat than BRPS, it is useful to include this comparison for basin-wide perspective. Overall passage efficiency through the facility was only 20% for juvenile subyearling Chinook, and 35.4% for juvenile yearling Coho. Results further suggest that

smaller fish, as well as those placed further away from the facility, are experiencing greater difficulty successfully passing BRPS.

The current facility may discourage fish passage as the fish passage facility entrance ports are generally deeper than the preferred rearing/migration depths of most juvenile salmonids, and do not have an adequate amount of flow to successfully attract juveniles. In addition, pump screening operations do not appear to exclude juveniles from entering pump turbines in some circumstances, which may create an additional source of mortality. Additionally, the facility creates a forebay that is intermittently drawn down and then filled again, creating unnatural and inconsistent flow patterns. Given the exposed and slow-moving nature of the forebay, this may result in both warmer water temperatures and conditions that favor non-native predator species (e.g., bass, sunfish, etc.) which are detrimental to juvenile salmonids. Upgrades to the facility should address these issues to ensure that flood risk reduction can occur without hindering salmon passage and survival. Interim modifications to the facility may also provide improved fish passage in the near term- including restoring operability of the airlift intake to the “high ports” which are located closer to the water surface where juvenile salmonids are more likely to find them, as well as ensuring all fish port sluice gates are open and operable. Overall, this study provides a better understanding of baseline conditions and demonstrates the critical need to upgrade downstream fish passage facilities at BRPS to support successful fish passage and to support subsequent salmon recovery throughout WRIA 9.

This page intentionally left blank.

## **1.0 INTRODUCTION**

---

The current downstream fish passage facility at the Black River Pump Station (BRPS) is the original system constructed in 1971. The downstream system consists of two rows of 5.25 inch × 5.25 inch square intake ports located in the pier walls that support pumps P1-P4, upstream of the pump exclusion screens. The ports are fitted with 6 inch x 6 inch cast steel sluice gates that are manually opened/closed by the station operators. These fish ports join into two separate conveyance pipes, which carry water from the upper or lower fish ports into the airlift bay. Here, the airlift pump injects air into each pipe via a sparge ring, which then leads vertically 52 feet into a de-aeration tank. The injection of air bubbles into the water reduces the density of water in the riser, which is pushed through the system by heavier (denser) water in the forebay, carrying flow and fish from the associated fish ports through the conveyance pipes. From the de-aeration tank, water flows via gravity through an 18-inch-diameter bypass pipe into the fish counting vault, then into the tailrace (Figure 1).

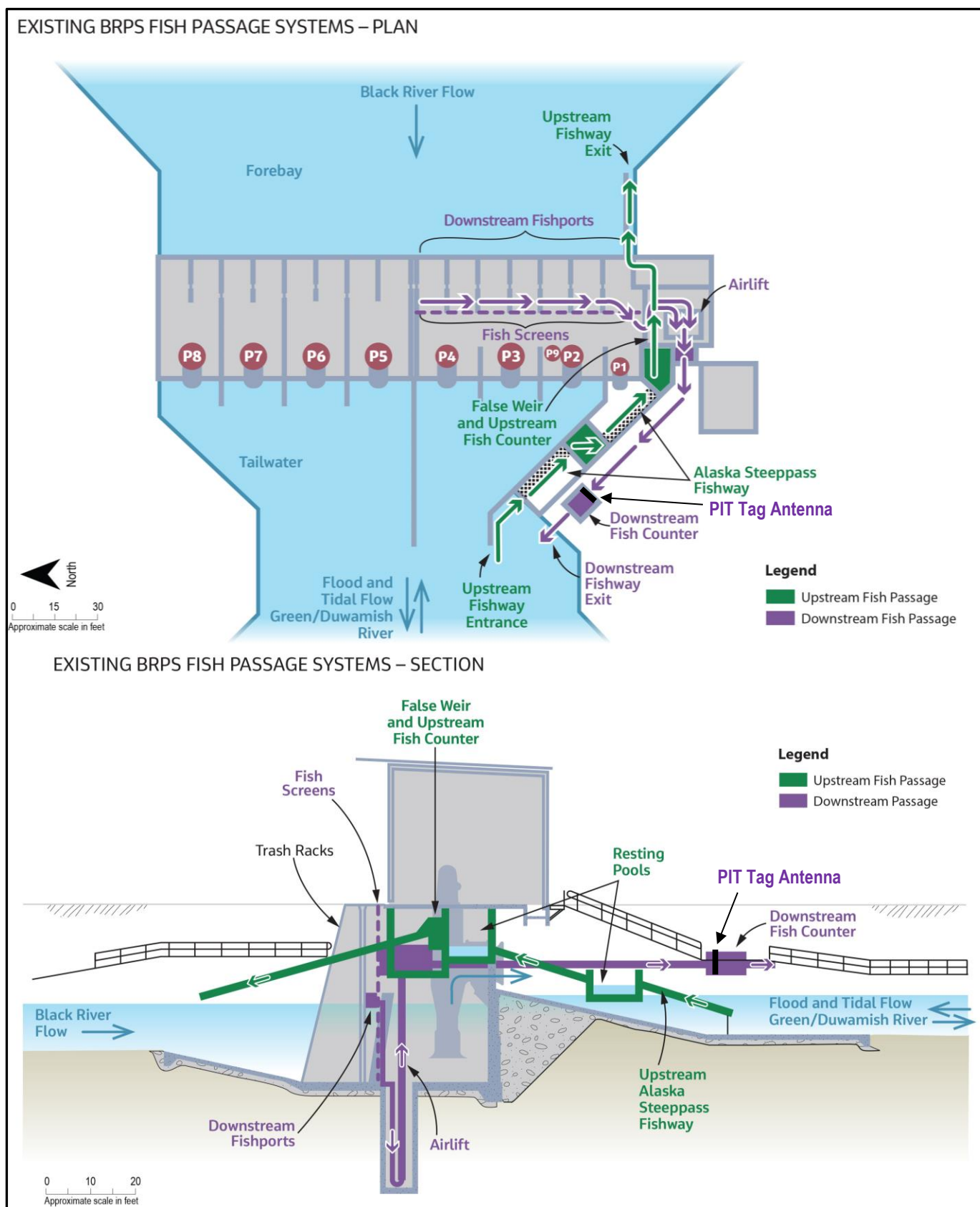
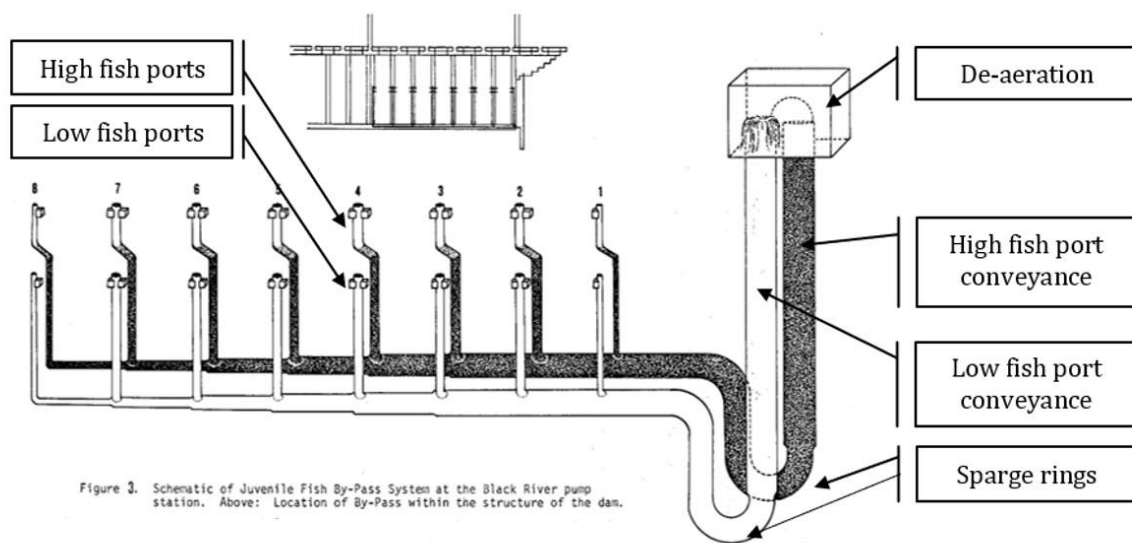


Figure 1. BRPS diagrams adapted from Jacobs (2020).

The two rows of square fish intake ports include a high row, and a low row- both fed by separate conveyance pipes into the de-aeration tank (**Error! Reference source not found.**). The high row is located at +5.5 ft NAVD88 and feeds the southern conveyance pipe in the airlift discharge basin and is currently inoperable for unknown reasons. The low row is located at +1.5 ft NAVD88 and feeds the northern conveyance pipe in the airlift discharge basin and was in service for the outmigration period in 2020. The duration for which the high ports have been inoperable is unknown. However, Tetra Tech (2015a) documented that the 3-inch air actuated three-way flow control valve (FCV-8) and associated solenoid valve (SV-8), which control air flow to either the high or low conveyance pipes, were inoperable in 2014. Because of this, both the low and high ports were in service at that time.



**Figure 2. Diagram of BRPS airlift high and low fish ports, conveyance pipes, and airlift de-aeration tank. Adapted from Fender (1979).**

Currently, the BRPS forebay is maintained at an elevation of 6.1 to 7.6 ft NAVD88 (Jacobs 2020). At this range, the currently functional lower fish ports are located approximately 4.55 to 6.05 ft below the forebay water surface. The non-functional upper fish ports are located 0.55 to 2.05 ft below the forebay water surface.

The two sets of fish ports (lower at 1.6 ft and upper at 5.6 ft NAVD88) were intended to allow passage for juveniles in the upper portion of the water column. However, the upper ports have not been working, even though the forebay water level has generally been sufficient for use of the upper ports. The BRPS operations manual (1972) states that the airlift system should function as follows: If the forebay water elevation is at the nominal 5.55 ft NAVD88, or between +1.55 and +6.05, then the lower airlift ports (elevation 1.55 ft) are operated. If the forebay elevation rises to +6.05, air supply for the airlift conveyance pipe is automatically switched to the upper fish ports (elevation 5.55 ft). If the upstream pool elevation drops below +1.55 ft or rises above +7.55 ft, the system is automatically shut

down. It is clear that the facility is currently not functional with regard to its designed operation.

TetraTech (2015) identifies testing of downstream facilities as a recommended fish migration action that is needed to improve facilities at BRPS. This includes determining the downstream overall passage efficiency (proportion of downstream migrating fish that successfully pass the facility) and measuring fishway migration efficiency using a fish tag and recapture protocol (FM-31). Understanding the effectiveness of the current facility is imperative for understanding the scope of work required to minimize the impacts of flood hazard management and bring BRPS fish migration facilities into regulatory compliance.

This study was approved as an early action item for the BRPS to provide valuable data regarding the functionality of the current structure. These data will help assess the efficacy of the current system in order to identify and prioritize future design changes. This will help ensure that appropriate design options and funding are targeted in an efficient and meaningful way.

**The purpose of this study is to:**

- 1) Examine the overall passage efficiency of the current downstream air lift facility using PIT (Passive Integrated Transponder) tagged yearling coho (*Oncorhynchus kisutch*) and subyearling Chinook (*O. tshawytscha*) salmon placed upstream of BRPS. Overall passage efficiency will be determined by calculating the proportion of the tag fish released upstream that are detected successfully passing through the entire downstream passage facility.
- 2) Examine differences in overall passage efficiency/timing of PIT tagged juvenile coho and Chinook salmon placed in different locations upstream of BRPS.
- 3) Examine residence time of PIT tagged juvenile coho and Chinook salmon upstream of BRPS.

**Key Terms:**

- **Detection Efficiency:** Also referred to as antenna detection efficiency. This term refers to the ability of the PIT tag antenna system to detect a tag that has passed through the PIT tag antenna detection field. This is expressed as a percentage and is calculated both manually through efficiency tests, and automatically by the reader itself. Efficiency tests require releasing tagged fish or fish surrogates directly into the field, then dividing the number of fish detected passing through PIT tag reader by the number of tagged fish introduced. In addition, detection efficiency is automatically calculated by the reader using a test tag frequency introduced into the field. Both methods were used in this study to ensure accuracy.
- **Overall Passage Efficiency:** A quantitative measure of the proportion of the PIT tagged population released upstream that successfully moves through the entire BRPS downstream fish passage system and are detected at the PIT tag antenna. This value is calculated by combining the actual tag detections (known detections) with the detection efficiency of the PIT tag array, which corrects for fish that may have passed the array but were not detected (unknown detections).

- **Attraction Efficiency:** A measure of the proportion of the population that successfully locates and enters the fish passage facility. Attraction efficiency can be broken into discovery efficiency (proportion of fish that locate the downstream entrance) and entrance efficiency (proportion of fish that discover the downstream facility entrance and enter). This was not measured in this study.
- **Retention Efficiency:** A measure of the proportion of the population that enters the fish passage facility and then successfully passes through it. This measurement helps understand the proportion of fish that may enter the facility but turn around and exit before successfully passing. This was not measured during this study.

## 2.0 METHODS

---

### 2.1 PIT System

A typical PIT tag study consists of several parts:

- 1) **PIT tag:** A pit tag is a small radio transponder sealed in an inert glass housing. This transponder consists of a small coil, which receives a “charge” from a PIT tag antenna. This charge powers an internal microchip, which then relays a unique identification number back to the antenna. Because a PIT tag obtains its energy from the antenna, it does not require a battery, which means that it can be manufactured for use in very small organisms and can last the lifespan of the organism. PIT tags are generally inserted into fish using a variety of sharp metal injectors, which leave a very small incision after tagging that quickly heals.
- 2) **PIT tag reader:** A PIT tag reader is a small computer board that powers the PIT tag antenna, interrogates signals received from the antenna, and stores data.
- 3) **PIT tag antenna:** A PIT tag antenna takes the signal produced by the PIT tag reader, emits it into the water, and interrogates any signal received back from PIT tags. Antennas are often produced from coils of wire tuned to a specific capacitance and can be tailored to the size required for the study as well as the read range of the specific size of PIT tag used.

The PIT tag system utilized for this study is a Biomark IS1001 reader board, which was placed near the counting vault in a secured box, fed by 120v power from BRPS. The antenna consisted of a simple pass-through system, which was temporarily fixed to the 18-inch-diameter gravity bypass pipe as it enters the counting vault (Figure 3). The reader/antenna system was operated continuously to detect tagged fish from March 24, 2020 to June 30, 2020, when the airlift system was shut down for the outmigration season. PIT tag detections were automatically recorded by the reader and downloaded manually once every 1 to 2 weeks throughout the study period.



**Figure 3.** PIT tag reader and antenna located at the downstream counting vault. Reader is enclosed steel box, and square pass through antenna (black pipe).

## **2.2 PIT Tagging Process**

Subyearling Chinook salmon (Soos Creek hatchery stock) and yearling Coho Salmon (Soos Creek stock) were obtained for the purpose of this study under WDFW permit #8293-03-09-20. Fish were picked up from the Soos Creek Hatchery on March 24, 2020 and transported via coolers to the Black River Pump Station. Water quality was monitored using a YSI sonde, and supplemental oxygen was used to keep dissolved oxygen concentration (DO) between 11 and 14 mg/L. A total of 169 subyearling Chinook and 104 yearling coho were obtained for this study. Mean fork length for these subyearling Chinook was 57.3mm (range 49–68mm), while mean length for yearling coho was 112.6mm (range 88–133mm).

Juvenile salmonids were tagged following the methods outlined by the Columbia Basin Fish and Wildlife Authority (2014). The four elements of the PIT tagging process outlined by CBFWA (2014) include:

1. Fish were collected/obtained prior to tagging.
2. Fish were taken from aerated coolers in small batches, anesthetized using MS222, and injected with PIT tags.
3. Information about each fish was recorded, and includes: injected tag number, species (coho or Chinook), fork length (mm), and release location (BRPS forebay, Springbrook Creek at Oakesdale Avenue SW, and the de-aeration tank for detection efficiency testing; Figure 4).
4. Fish were allowed to recover from the effects of tagging, handling, and anesthetic in water from the Green River (with supplemental oxygen) before they were released. This recovery period generally lasted 15 to 20 minutes.

The type of PIT tag used during this study was the Biomark HPT9 9mm 134.2 kHz ISO FDX-B RFID, EID. These tags are encapsulated in biocompatible glass and provide 100% unique identification. They are the highest performing RFID tag on the market today for fish and wildlife research in a 9mm size. The 9mm PIT tags are smaller than traditional 12mm PIT tags commonly used, allowing for the tagging of juvenile Chinook as small as 45mm, which is much smaller than previously possible. Compared to the 8mm PIT tag, the 9mm features a significantly higher read range, and is capable of open water detection by passive in-stream antennas (Matt Brower- Biomark, personal communication). Based on the passive antenna used for detection, the 9mm tag was chosen over the 8mm tag for this study.

## **2.3 Releasing Study Fish**

Following tagging, fish were allowed to fully recover in oxygenated water before being released. Fish were released in groups, by species and location. In order to examine differences in overall passage efficiency and timing of PIT tagged juvenile coho and Chinook salmon from different areas, coho and Chinook were released both in the BRPS forebay directly in front of the fish screens, and in Springbrook Creek immediately downstream of Oakesdale Ave SW (Figure 4) which is approximately 0.44 miles (0.7 km) upstream of the facility.



**Figure 4. Release Locations for PIT tagged coho and Chinook.**

A total of 145 subyearling Chinook were tagged for release above BRPS, with 84 released into the BRPS forebay and 61 into Springbrook Creek at Oakesdale. A total of 104 yearling coho were tagged as well, with 55 released into the BRPS forebay and 49 into Springbrook Creek at Oakesdale. Additionally, 23 subyearling chinook were tagged and released into the airlift de-aeration tank for detection efficiency testing.

## **2.4 Detection Efficiency Testing**

Detection efficiency testing was performed throughout the study period to describe overall performance of the antenna system for detecting PIT tagged fish passing through the downstream facility. The IS1001 reader used during this study features an automated detection efficiency test that can determine the overall efficiency of the antenna based on self-testing using a simulated tag signal introduced by the reader. This is done automatically each hour throughout the entire study period and is recorded and downloaded along with real tag detections. Because this is based on a simulated test tag, the actual amplitude of the tag signal produced may differ from that of a real tag passing through.

Detection efficiency tests were also conducted manually with real tags in conjunction with automatic efficiency testing in order to validate both methods. Initial antenna detection efficiency was tested by releasing 23 tagged Chinook directly into the de-aeration tank immediately following the upstream releases on March 24, 2020. Fish were released individually over a period of several minutes to reduce the possibility of tag collisions (tags not being detected due to multiple tags in the antenna field at the same time).

On April 1, 2020, inspection of the PIT antenna system revealed that the water levels in the counting vault were too low to allow for fish to pass through the counting ports, thereby trapping them in the vault (further discussed in section 3.5), and had been in this condition before the study began. Because of this, the counting ports located on the screening system stop logs were immediately removed to prevent further entrapment of fish in the counting vault (Figure 5). Changing the configuration of the counting vault changed the detection rate of the antenna. While the detection efficiency remained the same throughout the study, the ability to detect fish during the blockage was greatly increased as fish were trapped in close proximity to the antenna for an extended period of time. Due to the significant changes made near the antenna during the study, the detection efficiency test done on March 24 with live fish was only applied to the first 9 days of the study, before changes were made to the counting vault.



**Figure 5.** Counting vault condition during blockage before (left), and after 4/1 with counting ports and screen removed (right). Yellow arrows indicate inaccessible fish passage ports during blockage.

Following the change to the counting vault, further manual detection efficiency tests were done to validate automatic detection efficiency testing following the removal of the counting system. A total of 10 manual detection efficiency tests were conducted throughout the study period using 20 PIT tags inserted into 1" cubes of Styrofoam material, as live fish were no longer available from WDFW. These test tags were then placed into the 18" gravity bypass pipe exiting the discharge basin. Tags were released individually, 15 seconds apart in order to prevent tag collisions. Detection efficiency was then calculated by dividing the number of test tags detected by the antenna by the 20 total tags.

Reader-generated antenna efficiency from April 1 to June 30 was obtained from calculating the mean and 95% confidence interval for all hourly records of automatic detection efficiency recorded throughout the study. This value was then validated using results from the 10 manual efficiency tests. Except for the period from March 24 to April 1, all test results were grouped together to calculate a single detection efficiency rather than applied over the time span they were collected because conditions at the antenna were consistent throughout the study period (same flow and operating conditions).

## **2.5 Tag Retention and Mortality**

During a typical PIT tag study of this nature, a control group of tagged fish is kept in captivity to monitor the rate of delayed mortality and tag rejection (tag is expelled by a live fish). During this study, however, WDFW COVID-19 protocols prevented us from keeping and accessing live fish at the Soos Creek hatchery for continued monitoring. Because of this, all tagged fish were released the same day as tagging. In order to account for potential mortality and tag rejection, literature values were used in lieu of captive observations. Tiffan et al. (2015) states that juvenile Chinook 50–59mm in length tagged using the same 9mm PIT tag used for this study had tag rejection rates averaging 3.3%, and zero mortality (<1% for all sizes). Larger size classes had lower mortality and higher rates of tag retention, so for the purpose of this study these numbers are likely conservative for yearling coho. To account for all unknown mortality related to PIT tagging as well as tag rejection, a conservative value of 5% combined mortality and tag rejection was applied to all coho and Chinook release groups. This was done by excluding 5% of the total number of fish released from the overall passage efficiency calculations. If this 5% conservative value is greater than what occurred during this study (as the literature suggests), actual passage rates would be slightly lower than what is reported here.

## **3.0 RESULTS**

---

### **3.1 PIT Antenna Detection Efficiency**

The PIT antenna and reader system was installed in the fish counting vault on March 24, 2020, and was capacitance tuned specifically for site conditions. Even with proper tuning of the small pass through antenna, the antenna experienced consistent environmental “noise,” which prevented complete detection of tagged fish. This noise is generally the result of unwanted in-band external signals and electromagnetic interference. In addition, ferrous metals in the vicinity of the PIT antenna can interfere with the electromagnetic communication between the PIT reader and tags. While this is largely unavoidable at a site like BRPS, the actual detection of the efficiency of the antenna was adequate for this study.

Initial detection efficiency testing used tagged Chinook on April 1 while the counting vault was blocked, which resulted in a total of 19 of 23 tagged fish being detected for an overall antenna detection efficiency of **82.6%** (Table 1). This value was applied to all tag detections from March 24 to April 1 to calculate passage success for this time period. We assume that no fish died between release and detection as fish were released near the antenna with no hazards or barriers present. Detection efficiency was much higher during the blockage versus afterwards for the following reasons:

- 1) The blockage within the counting vault prevented fish from easily passing through, which greatly increased the amount of time that fish were present near the antenna.
- 2) After the blockage was removed, the water level within the counting vault dropped below the antenna. Because of this, fish were not likely to be detected again after passing the antenna.

From April 1 to June 30, when the counter was removed and passage was restored, detection efficiency tests conducted automatically by the reader resulted in 1866 unique tests completed with a mean efficiency of **29.6%** (95% confidence interval 29.4–29.8%). This value was applied to all tag detections from April 1 to June 30 to calculate passage success for this time period. Detection efficiency based on the 10 manual efficiency tests was **29%** (95% confidence interval 24.66–33.34%), which validates the automatic detection efficiency value produced by the reader (Table 1).

**Table 1. Detection efficiency tests conducted during the study.**

Trial	Test Type	Counting Vault	Date	Efficiency
1	Live Fish	Blocked	24-Mar	82.6%
2	Test Tag	Open	22-Apr	35.0%
3	Test Tag	Open	22-Apr	30.0%
4	Test Tag	Open	22-Apr	25.0%
5	Test Tag	Open	6-May	40.0%
6	Test Tag	Open	6-May	25.0%
7	Test Tag	Open	6-May	40.0%
8	Test Tag	Open	15-Jun	20.0%
9	Test Tag	Open	15-Jun	20.0%
10	Test Tag	Open	15-Jun	25.0%
11	Test Tag	Open	15-Jun	30.0%
<b>3/24/20-4/1/20</b>		<i>Manual Efficiency</i>		<b>82.6%</b>
<b>4/1/20-6/30/20</b>		<i>Automatic Efficiency (95% C.I.)</i>		<b>29.6% (±0.2%)</b>
<b>4/1/20-6/30/20</b>		<i>Manual Efficiency (95% C.I.)</i>		<b>29% (±4.34%)</b>

## 3.2 Overall Passage Efficiency

Overall passage efficiency is calculated from the product of two probabilities: the probability of surviving and being detected passing through the entire BRPS airlift system, and the probability of being detected by the PIT reader/antenna. Detection efficiency test results were applied to the number of actual tag detections for both the time period during the blockage (82.6% efficiency) and afterwards (29.6% efficiency) to correct for fish that passed the antenna but were not detected. The following formula was used for each species and release location:

$$\left( \frac{100 * \text{Tag Detections}}{\text{Antenna Efficiency (82.6\%)}} \right)^{3/24-4/1} + \left( \frac{100 * \text{Tag Detections}}{\text{Antenna Efficiency (29.6\%)}} \right)^{4/1-6/30} = \text{Overall Passage Efficiency}$$

(Total Fish Released - 5% Assumed Mortality and Tag Rejection)

Of the **145** subyearling Chinook tagged and released above BRPS, a total of **12** were detected passing through the downstream passage facility resulting in an overall passage success rate of **20.0%** (Table 2). Passage success for Chinook released into the BRPS forebay was **26.0%** (**10 of 84** detected), while passage success for Chinook released into Springbrook at Oakesdale was **7.9%** (**2 of 61** detected).

Of the **104** yearling coho tagged and released above BRPS, a total of **20** were detected passing through the downstream passage facility resulting in an overall passage success rate of **35.4%** (Table 2). Passage success for coho released into the BRPS forebay was **40.9%** (**14 of 55** detected), while passage success for coho released into Springbrook at Oakesdale was **29.3%** (**6 of 49** detected).

**Table 2. Overall passage efficiency calculations for all Chinook and coho released upstream of BRPS.**

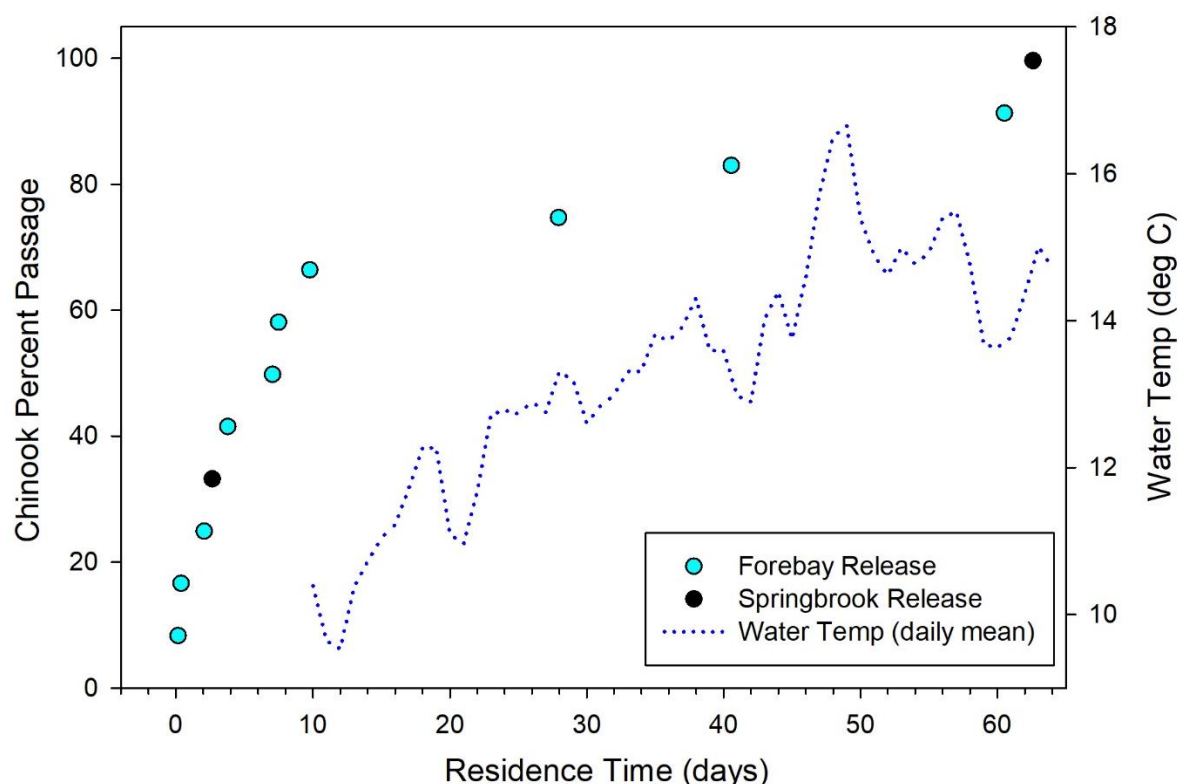
<b>Chinook</b>	<b>Release Location</b>		<b>Total</b>
	<b>BRPS Forebay</b>	<b>Springbrook @ Oakesdale</b>	
<i>Total Tagged</i>	84	61	145
<i>Assumed tag mortality + rejection rate*</i>	5%	5%	5%
<i>Antenna Efficiency 3/24-4/1</i>	82.6%	82.6%	82.6%
<i>Antenna Efficiency 4/1-6/30 (95% CI)</i>	29.6% ( $\pm 0.2\%$ )	29.6% ( $\pm 0.2\%$ )	29.6% ( $\pm 0.2\%$ )
<i>Tags Detected</i>	10	2	12
<b>Passage Success</b>	<b>26.0%</b>	<b>7.9%</b>	<b>20.0%</b>
<i>95% CI based on antenna efficiency</i>	(25.86-26.09%)	(7.87%-8.00%)	(19.85%-20.05%)

<b>Coho</b>			
<i>Total Tagged</i>	55	49	104
<i>Assumed tag mortality + rejection rate*</i>	5%	5%	5%
<i>Antenna Efficiency 3/24-4/1</i>	82.6%	82.6%	82.6%
<i>Antenna Efficiency 4/1-6/30 (95% CI)</i>	29.6% ( $\pm 0.2\%$ )	29.6% ( $\pm 0.2\%$ )	29.6% ( $\pm 0.2\%$ )
<i>Tags Detected</i>	14	6	20
<b>Passage Success</b>	<b>40.9%</b>	<b>29.3%</b>	<b>35.4%</b>
<i>95% CI based on antenna efficiency</i>	(40.84%-41.02%)	(29.15%-29.44%)	(35.29%-35.52%)

### 3.3 Passage Timing

PIT tagged subyearling Chinook that were detected successfully passing the BRPS downstream facility did so in a mean time of **18.7 days**, ranging from **0.2 to 62.4 days** (Figure 6). Of the 12 Chinook detected, 66.7% were detected passing in the first 10 days following release. Mean passage time for the 10 Chinook detected from the forebay release group was **16 days** (range 0.16 to 60.5), while mean passage time for the two Chinook detected from the Springbrook release group was **32.6 days** (2.66 and 62.9). Low sample size for Chinook detected from the Springbrook group prevents statistical comparison among the two groups but is provided for basic insight.



**Figure 6. Actual tag detection times for all tagged Chinook detected successfully passing the BRPS downstream facility. Water temperature at King County gage 03G (0.44 miles/0.7 km u/s of Oakesdale release site, 0.9 miles/1.4 km u/s of BRPS)**

PIT tagged yearling coho that were detected successfully passing the BRPS downstream facility did so in a mean time of **5.8 days**, ranging from **0.4 to 27.4 days** (Figure 7). Of the 20 coho detected, 85% were detected passing in the first 10 days following release. Mean passage time for the 14 coho detected from the forebay release group was **2.65 days** (range 0.42 to 9.33), while mean passage time for the 6 coho detected from the Springbrook release group was **13.2 days** (range 1.57 to 27.37). This difference is statistically significant (Mann-Whitney test  $p=0.009$ ), with coho from the Springbrook at Oakesdale release taking longer, on average, to pass BRPS than those released into the forebay.

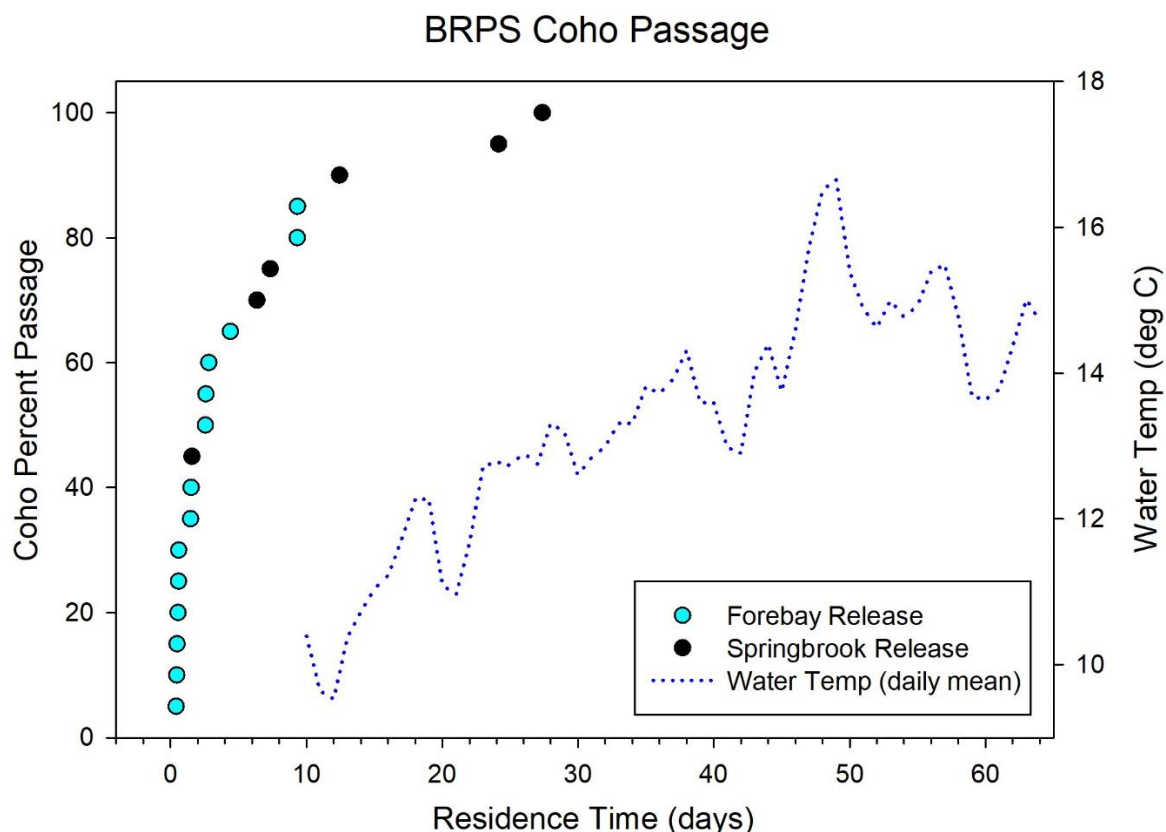
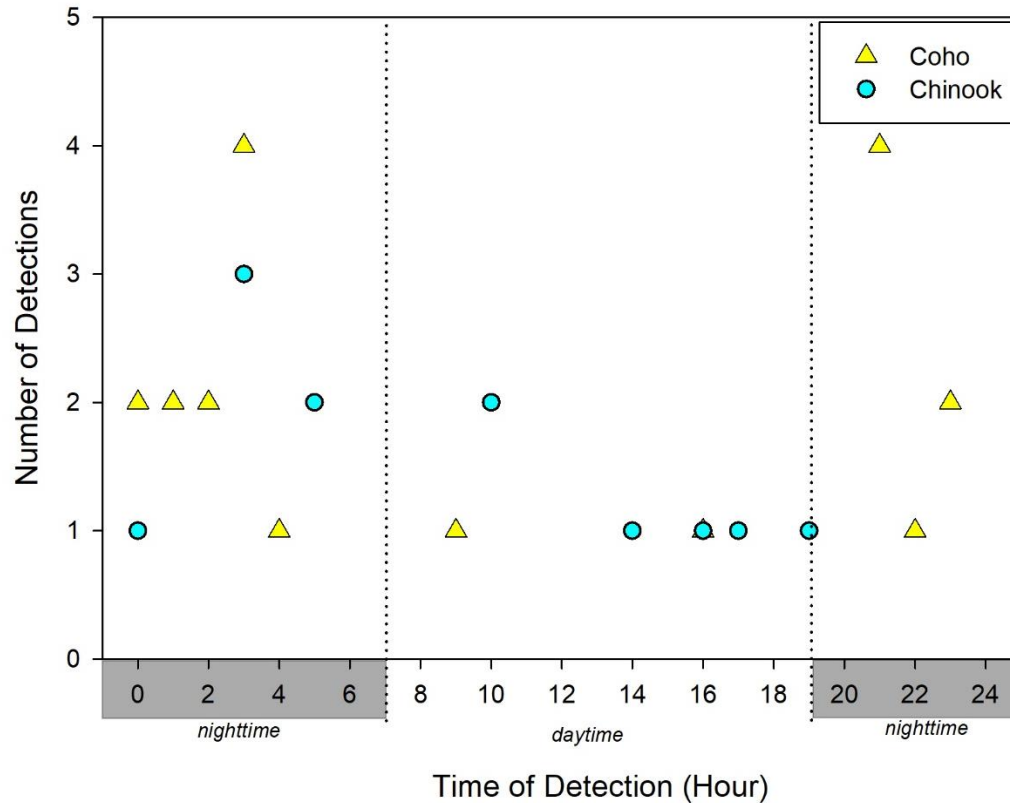


Figure 7. Actual tag detection times for all tagged coho detected successfully passing the BRPS downstream facility. Water temperature at King County gage 03G (0.4 miles/0.7 km u/s of Oakesdale release site, 0.9 miles/1.4 km u/s of BRPS)

### 3.4 Diel Movement of Fish through BRPS

Day and night movement of tagged juvenile Chinook and coho was analyzed to explore patterns in timing of fish passing through the BRPS downstream facility (Figure 8) given out-migrating salmonids are known to preferentially migrate during night hours. Juvenile Chinook passed through the facility between 12am (midnight) and 7pm, with half of detections occurring in the 5 hour window between 12am and 5am, while the other half of the detected Chinook passed through the 14 hour window between 5 am and 7pm. Juvenile coho largely passed through the facility at night, with all but 2 detections occurring during the 7-hour window between 9pm and 4am.



**Figure 8. Diel detections of juvenile Chinook and coho detected moving through the BRPS downstream facility.**

### 3.5 Downstream Fish Counting Vault Blockage

While the blockage in the downstream fish counting vault from March 24 to April 1 complicated passage calculations and efficiency testing, it also provided a unique opportunity to assess fish (both wild and tagged) that were present in the downstream passage system. Immediately upon discovering the problem, both live and dead fish were salvaged from the counting vault, and the airlift pump was shut down to assess the issue. Fish captured in the vault were documented, which included number, species, tag presence, and disposition (Table 3). Species included coho (yearling), coastal cutthroat trout (*Oncorhynchus clarkii clarkii*), and steelhead (*Oncorhynchus mykiss*). Steelhead were distinguished from resident rainbow trout by their color pattern, which indicated that they had begun smolting. Following capture and enumeration, all fish were released into the BRPS tailrace.

**Table 3. Fish captured following downstream counting vault blockage.**

Species	Origin	Disposition	Injuries	Fork Length (mm)	Pit tag present	Release Location
Coho	hatchery	Dead	Descaled	117	Yes	Springbrook
Coho	hatchery	Dead	Descaled	121	Yes	Springbrook
Coho	wild	Dead	Descaled	123	No	
Coho	wild	Live		118	No	
Coho	wild	Live		119	No	
Coho	wild	Live		117	No	
Coho	hatchery	Live		119	Yes	Forebay
Coho	hatchery	Live		110	Yes	Forebay
Coho	hatchery	Live		113	Yes	Forebay
Coho	wild	Live		125	No	
Cutthroat Trout	wild	Dead		178	No	
Cutthroat Trout	wild	Live		185	No	
Steelhead	wild	Live		215	No	
Steelhead	wild	Live		215	No	
Steelhead	wild	Live		224	No	
Steelhead	wild	Live		236	No	
Steelhead	wild	Live		214	No	
Steelhead	wild	Live		224	No	
Steelhead	wild	Live	Descaled	136	No	

Overall, three of the 10 coho removed from the counting vault were deceased, one of the two cutthroat trout were deceased, and all seven steelhead captured were live (Figures 9 and 10). Some fish showed signs of major descaling, however given the good overall condition of most live fish- this was likely from entrapment in the counting vault rather than descaling associated with the airlift system itself. Additionally, 10 of the 15 PIT tagged coho and 6 PIT tagged Chinook detected in the counting vault during the March 24 to April 1 blockage were not found. Because of this, their final disposition (live or dead) is unknown. Fish, especially the smaller Chinook, may have been able to escape, may have been consumed by the larger steelhead smolt, or may have decomposed and washed through the small cracks in the counting vault.

Entrapment time for PIT tagged fish detected in the counting vault during the 3/24 to 4/1 blockage was enumerated by subtracting the last from the first recorded detection. Coho were trapped in the counting vault an average of 45 hours 13 minutes (range 11 minutes to 7 days 6 hrs.). The two dead PIT tagged coho observed in the counting vault had been there 35 hours and 11 hours, respectively. Chinook were trapped in the counting vault an average of 22 minutes (range 0 to 1 hr. 31 minutes).



**Figure 9.** Deceased coho observed during the counting vault blockage, including two PIT tagged hatchery fish (top and middle), and one wild fish (bottom).



**Figure 10.** Wild steelhead smolt observed during the counting vault blockage.

## 4.0 DISCUSSION AND CONCLUSIONS

---

The 20% overall passage efficiency of Chinook and 35.4% overall passage efficiency of coho at the Black River Pump Station demonstrates the critical need for updated downstream fish passage technology at this facility. While this does not address attraction or retention efficiency, it provides useful insight to the overall success of current downstream passage at BRPS. NOAA (National Oceanic and Atmospheric Administration) recently published a biological opinion for downstream fish passage at Howard Hanson Dam (NOAA Fisheries 2020), which states that design of the new fish passage facility must provide:

- An overall juvenile fish project passage survival rate of **75%**, from entry into Eagle Gorge reservoir to release points downstream. (*Overall Passage Efficiency—similar to what was measured during this study*)
- 95% collection of fish attracted to the fishway. (*Attraction efficiency—not measured at BRPS for this study*)
- 98% survival of fish through the facility to their release downstream. (*Retention efficiency/survival—not measured at BRPS for this study*)

While the habitat quality and quantity vary significantly between the areas affected by HHD and BRPS, the affected species belong to the same evolutionary significant units and therefore are managed by the same recovery goals. The current passage rates observed during this study at BRPS are below the 75% requirement at HHD (which may be applicable to other downstream passage facilities in WRIA 9), and in its current status is likely limiting salmon production and recovery throughout the Black River/Springbrook subbasin and to a lesser extent the Green River as a whole.

During this study, different levels of overall passage efficiency were observed for both coho and Chinook that were released into the BRPS forebay versus into Springbrook Creek at Oakesdale. The overall passage efficiency for Chinook was 26% for fish released into the BRPS forebay, while only 8% for those released into Springbrook Creek. For Coho, overall passage efficiency was 41.2% for fish released into the BRPS forebay, while only 29.7% for those released into Springbrook. While an overall passage efficiency is lower for both species released further upstream, the disparity is higher for Chinook. This may be the result of smaller juvenile salmonids experiencing greater difficulty locating the downstream passage facility entrance ports.

Juvenile coho and Chinook released into Springbrook Creek were far less likely to be detected successfully passing the BRPS facility. While the difference in overall passage efficiency for fish released in the forebay versus Springbrook cannot be attributed to specific variables (inability to find the passage facility, mortality associated with predation or delayed migration, sublethal temperature impacts, water quality impacts, potential to rear as yearlings, etc.), there are differences in passage patterns for fish that were detected successfully passing. These impacts may stem from the artificial conditions created by the BRPS forebay and/or poor attraction efficiency, which could be potentially mitigated by

different design options. For Chinook, the two groups experienced a similar range of time for detected fish to pass the facility (0.16 to 60.5 days for forebay fish versus 2.66 to 62.9 days for Springbrook fish), though the detection of only two Chinook from Springbrook makes an accurate comparison difficult. For coho, the first fish detected from each release location were only a day apart (0.42 vs 1.57 days); however, the last fish detected varied much more—9.33 days for coho released in the forebay versus 27.37 days for those released in Springbrook.

In conjunction with overall passage efficiency, differences in passage time were also observed. Mean passage time for coho was 5.8 days, whereas mean time for Chinook was 18.7 days. One potential cause of the difference in time is due to typical outmigration timing, as Chinook parr generally out-migrate slightly later than yearling coho in the Green River (Topping and Anderson 2018).

Fender (1979) performed a similar study at the Black River Pump Station by releasing 20,000 chum fry into the forebay and collecting fish that successfully passed through the airlift system into a net at the downstream end. This study showed that only 6% of chum fry successfully passed through the facility (up to 11% if adjusted for missing fish). Of this 6% that successfully passed, 61% experienced a minimum delay in migration of 20 days or more.

When taking the results of this study into account with the results of Fender (1979), there may be size-selective differences in overall passage efficiency through the system with larger fish (such as yearling coho) experiencing higher passage rates than smaller fish. While the exact factors influencing the low overall passage efficiency for smaller fish are difficult to determine, a few factors provide valuable insight:

- Fender (1979) discovered that the mesh size of the BRPS pump screens were sufficiently large enough for chum fry less than 50mm to pass through. This means the fry would have to go through the turbines to reach the Green River, and not go through the fish ports and lift system. Survival of this passage route is likely very low. It should be noted that ESA-listed Chinook fry found in the larger Green River system frequently migrate downstream to the Duwamish at sizes below 50mm. While the screens were replaced in approximately 2012, Jacobs (2020) documents that the screen material and opening size currently do not meet federal criteria. This may play a major role in reduced passage success for smaller fish.
- Fender (1979) stated that the most probable cause of reduced system efficiency was found to be insufficient attraction flow, with only 0.08 f/s water flow being measured at the bypass intake orifices. Jacobs (2020) documents that the current downstream passage system does not meet current attraction flow and velocity criteria.
- Pump screen malfunctions occurred during the study. These screens keep fish out of the pumps, which were not designed for safe fish passage. During these outages, the automated mechanical cleaning systems failed to redeploy the screens after cleaning, leading to open pumping of the forebay. This active pumping is likely

attractive to downstream migrating salmonids, and when left unscreened can draw any nearby fish through the pump turbines. Fish passed through the pump turbines likely have a low survival rate. Additional work is being planned to evaluate fish mortality associated with passage through the pumps.

- Entrances to the fish ports may be too deep for many fish to successfully find. The current locations of airlift fish ports are at +5.5 ft (high ports) and +1.5 ft NAVD 88 (low ports). Currently, only the low ports are functional, which means at normal forebay levels, the fish port entrances are located approximately 4.5 to 6 ft below the forebay water surface. Optimum depths for juvenile Chinook in turbid water (such as that found at BRPS) have been found to be less than 0.5 ft deep (Suchanek et al. 1994), and data indicate that in turbid water, salmonids will use shallower water than typical for clear water. Kennedy and Strange (1982) found that yearling salmonids (such as coho) were found in a wider range and deeper depths than subyearling fry, most of which were found in water less than 20cm (0.65 ft) deep. This may provide a partial explanation for the higher overall passage efficiency for the larger yearling coho found in this study. Juvenile salmonids are generally surface-oriented as they out-migrate, and because of this, surface spill is more effective for their downstream migration (Johnson and Dauble 2006).
- Mortality associated with delayed migration. While not measured during this study, delayed migration caused by inability to locate downstream fish passage in the BRPS forebay would logically create a greater risk of mortality over time due to predation or impacts of poor water quality. During this study, water temperatures in Springbrook Creek upstream of the BRPS forebay did not exceed 17.5°C (the state standard for salmonid spawning, rearing, and migration for this area). While the temperatures did not exceed state standards upstream of the project area, we cannot say whether or not they did within the study area, which likely has higher temperatures due to exposure and low flows in the BRPS forebay. It is possible that different water management strategies within the forebay (i.e., changes in forebay elevation) may reduce these impacts and should be explored.

During the repairs to the blocked counting vault on April 1, only coho, steelhead, and cutthroat were found. Operation of the downstream passage facility may select for species that out-migrate at larger sizes, which are better suited for navigating the current downstream facility. Adult Chinook, coho, and steelhead have been observed upstream of the BRPS facility (Harza 1995, Kerwin and Nelson 2000). While these are the primary species that have been observed, the Black River subbasin features habitat that is suitable for chum and pink salmon as well. Though these species are the two most populous salmon species in WRIA 9, they have not been documented in the Black River subbasin. This may be due to the inability of surface-oriented fry to migrate downstream through the BRPS, as entrance ports are located deeper than their migration path. Chum and pink salmon migrations occur at night, and downstream movement is mainly at or close to the surface (Neave 1955; Hoar 1956). In addition, the small size of chum and pink fry likely prevent the current pump screens from successfully keeping fry out of the pump turbines.

In addition to the results of this study, the counting vault blockage provides unique insight for wild salmonids passing through the facility. While this blockage had obvious temporary impacts to fish migration, Chinook seemed to pass through relatively quickly despite the blockage, and we speculate that most of these fish likely survived. Due to the long residence time of tagged coho found in the counting vault during the blockage and the presence of dead coho, it is likely that larger yearling-size fish experienced higher mortality rates. Despite this incident, it appeared that most fish were in good overall condition and is suggestive that the airlift facility is not inflicting injury to fish that are passing through. Harza (1995) noted that coho sampled traveling through the facility seemed healthy and showed few signs of physical damage from the airlift facility. Harza (1995) also documented juvenile rainbow trout/steelhead and coho from the Green River migrating up the adult fish ladder into the BRPS forebay. This known behavior makes it even more critical to update fish passage at BRPS, as it may be creating a source of mortality for juvenile salmon from outside as well as inside the Black River subbasin under current conditions.

## **4.1 Caveats**

- Due to the COVID-19 pandemic, fish had to be picked up from the hatchery with only one day's notice before the hatchery was closed to outside staff due to COVID-19 concerns. Because of this, fish were transported, tagged, and released the same day. Under optimal conditions, fish would be tagged and held for 24 hours to determine tag retention and post-tagging mortality rates; however, this was not possible for this study. Because of this, we used published tag retention and mortality rates suitable for the methods used in this study.
- While a PIT tag study of this nature is effective for understanding the overall passage efficiency of the entire structure, it only provides insight for the facility as a whole. It does not provide information regarding attraction or retention efficiency. Utilizing acoustic tracking could answer these questions; however, studies such as this that use small subyearling Chinook are largely limited to PIT tags which would require additional antennas and have the additional caveat of imperfect detection (difficult to quantify in open water areas like the BRPS forebay).
- Subyearling Chinook that were not recorded passing the downstream facility before it closed on June 30 could possibly stay and rear, exiting as yearlings in 2021. While the proportion of fish exhibiting this life history strategy is likely low, it is a possibility. Running the PIT tag antenna during the 2021 operation would allow us to determine if this is occurring.
- Because of the rushed timeline, implementing downstream netting to determine fish condition was not possible for this study. While blockages in the counting vault allowed for some data collection regarding fish condition, further study of fish condition should be done if portions of this facility will be used in the future.
- The potential impacts of the BRPS on upstream water quality and species composition are not well documented. Assumptions around predation rates and potential temperature/water quality impacts should be treated with caution and further explored.

## **5.0 RECOMMENDATIONS**

---

### **5.1 Near-term Actions**

- Restore fish passage to the “high” fish ports only. Due to the consistent operation of the airlift pump, splitting the passage between both the upper and lower ports likely provides reduced attraction flow to each port and is not recommended. Restoring passage to the high ports likely involves the replacement of flow control valve FCV-8, as well as solenoid SV-8, which were stated to be inoperative in 2014 (Tetra Tech 2015). At some point in the past, the SV-8 solenoid was taken out of service and the flow control valve FCV-8 was manually adjusted to allow airflow to both airlift pumps. At this time, however, only the low ports are active. Changing to the high ports would allow fish passage to be better aligned with preferred depths of juvenile salmonids and utilizing only the high ports would ensure that the greatest attraction flow possible is provided to each of the fish ports. Maintaining operability of the low ports is important as well, as water levels occasionally drop below the high ports. Alternatively, forebay elevation may be managed to keep the high ports submerged.
- Assure that the steel sluice gates on each of the forebay fish ports are open and not blocking/limiting fish passage. This may be accomplished by lowering the forebay water surface elevation below +1.55ft NAVD88, raising the fish screens, and visually inspecting each sluice gate from the catwalk in the pump bays.
- Operate the downstream fish passage facility whenever possible. Given the presence of rearing coho, cutthroat trout, and steelhead throughout the summer, operation of the airlift system year-round (as inflow allows) would provide an outlet, should fish seek to move to the mainstem river as they grow or if water quality becomes unsuitable in the forebay during the summer months. In addition, this provides a longer window for fish that are having difficulty locating the current downstream passage entrances.
- Install water temperature loggers in the upstream and downstream fish passage facilities to determine if and when water quality may be affecting fish passage at the facility.

### **5.2 Implications for Fish Passage Facility Design**

- Future downstream passage facilities should feature an entrance that can operate under variable forebay water elevations and provide easy access for shore/surface oriented juvenile salmonids. This entrance should be sufficiently large (and surface oriented) with appropriate attraction flow to be detected by out-migrating juvenile salmonids easily.
- Incorporate a bypass and fish retention facility into the downstream passage design that can capture and hold downstream migrants. This will enable fish to be temporarily held for future monitoring, marking, and enumeration. Such systems are common in downstream passage facilities and will greatly aid in assessing the

system's function throughout its lifespan, as well as ensuring permit compliance. Currently, the only way to capture fish migrating through the BRPS downstream facility is with a floating net pen at the outlet of the downstream passageway, which is extremely labor-intensive, inefficient, and may injure fish (Fender 1979).

- Explore design options that may reduce potential impacts of the artificial forebay on juvenile salmonid survival and overall passage efficiency. These potential impacts, such as poor water quality and improved habitat for predators, may be reduced by allowing cool, clean water from the Green River to regularly flush into the forebay when allowable. In addition, reducing the size and water elevation of the forebay may alleviate some of these issues by reducing the amount of artificial habitat, therefore reducing habitat for predators (though would inhibit volitional passage options).

### **5.3 Future Monitoring Recommendations**

- Evaluate the potential impacts of unscreened pumping in future design options. This must include quantifying the survival rate of fish passing through each type of pump, as well as understanding fish presence in the forebay at times when pumping occurs. Survival rates of fish passing through the unscreened pumps could be evaluated utilizing sensor fish (<https://atstrack.com/tracking-products/transmitters/ARC800-Sensor-Fish.aspx>) and/or micro-acoustic tagged live fish. Various survey methods (e.g., seining, trapping, electrofishing) could evaluate fish presence in the forebay. These data are essential for documenting any incidental take associated with pumping operations and screen outages, as well as any design option that includes unscreened pumping.
- Some juvenile salmonids likely spend the winter holding and rearing in the BRPS forebay near the low-use pumps. Even if these salmonids are not actively out-migrating while these pumps are in use, there is a high potential for them to be near pumps throughout the flood season when low-use pumps are activated. As mentioned previously, Harza (1995) documented juvenile rainbow trout/steelhead and coho from the Green River emigrating into the BRPS forebay through the adult fish ladder during the fall and winter months, likely staying until the following spring. Movement of these species into off-channel areas during the fall and winter is common in the Green River basin (Harza 1995). Understanding the potential impacts of unscreened pumping is critical in consideration and prioritization of pump station improvements so that impacts can be minimized and salmonid species can be protected.
- Conduct netting of downstream passage facility as originally planned for 2020 to determine condition factor, as well as document natural-origin fish passing through the system.
- Perform micro-acoustic tracking to gain a better understanding of juvenile salmonid downstream facility attraction efficiency (and related discovery/entrance efficiency), as well as retention efficiency. See key term definitions in section 1.0.

- Assess water quality and temperature in the BRPS forebay and upstream tributaries to understand their potential impacts on juvenile and adult salmonids.
- Conduct surveys (e.g., eDNA, gillnetting, spawning surveys, electrofishing) to document species composition within the reservoir and upstream tributaries to better quantify potential predation impacts associated with the BRPS forebay and design options that may influence forebay area.
- Additional PIT tagging studies of this nature should incorporate additional PIT tag antennas. An antenna placed further upstream, with fish released above multiple antennas, would provide information regarding travel time in Springbrook Creek versus the BRPS forebay. In addition, antennas at the entrance ports to the downstream passage facility could provide more information regarding attraction and retention efficiency.
- Perform PIT tag testing using multiple groups released throughout the fall/winter/spring in order to understand overall passage efficiency over time at a variety of flow and pumping conditions.

## **6.0 REFERENCES**

---

- Beecher, H.A., B.A. Caldwell, and S.B. DeMond. 2002. Evaluation of depth and velocity preferences of juvenile coho salmon in Washington streams. *North American Journal of Fisheries Management*. 22:785-795.
- BRPS Operations Manual. 1972. Green River Flood Control District Black River Pumping Plant Operations and Maintenance Manual Book. United States Department of Agriculture Soil Conservation Service. Spokane, WA.
- Fender, D.C. 1979. Preliminary evaluation of the black river juvenile fish bypass system. US Fish and Wildlife Service, Olympia, WA.  
<https://www.fws.gov/wafwo/fisheries/Publications/FP043.pdf>
- Fisheries, NOAA. 2020. Biological Opinion on Howard Hanson Dam, Operations, and Maintenance, Green River (HUC17110013) King County, Washington. NOAA's National Marine Fisheries Service, Northwest Region. Seattle, WA
- Hoar, W.S. 1956. The behaviour of migrating pink and chum salmon fry. *Journal of the Fisheries Board of Canada*, 13(3), 309–325.
- Harza. 1995. Comprehensive fisheries assessment of the Springbrook, Mill and Garrison Creek watershed for the City of Kent. Prepared for City of Kent, WA.
- Jacobs. 2020. Black River Pump Station Improvements, Phase 1: Fish Exclusion and Fish Passage. Prepared for King County Water and Land Resources Division. Seattle, WA.
- Johnson, G.E., and D.D. Dauble. 2006. Surface flow outlets to protect juvenile salmonids passing through hydropower dams. *Rev. Fish. Sci.* 14, 213–244.
- Kerwin, J., T. Nelson. 2000. Habitat limiting factors and reconnaissance assessment report. Green/Duwamish and central Puget Sound watersheds (WRIA 9 and Vashon Island). Washington Conservation Commission and King County Department of Natural Resources. Seattle, Washington.
- Kennedy, G.J.A., and C.D. Strange. 1982. The distribution of salmonids in upland streams in relation to depth and gradient. *Journal of Fish Biology*, 20(5), 579-591.
- Neave, F. 1955. Notes on the seaward migration of pink and chum salmon fry. *Journal of the Fisheries Board of Canada*, 12(3), 369-374.

Suchanek, P.M., R.P. Marshall, S.S. Hale, and D.C. Schmidt. 1984. Juvenile Salmon Rearing Suitability Criteria. Alaska Department of Fish and Game. Anchorage, AK.

TetraTech. 2015. Black River Needs Assessment and Capital Improvement Planning. Prepared for King County Water and Land Resources Division. Seattle, WA.  
<https://your.kingcounty.gov/dnrp/library/water-and-land/flooding/green-river/black-river-pump-station-needs-assess-task-4-2015.pdf>

Tiffan, K.F., R.W. Perry, W.P. Connor, F.L Mullins, C.D. Rabe, and D.D. Nelson. 2015. Survival. Growth, and tag retention in Age-0 Chinook salmon Implanted with 8-, 9-, and 12-mm PIT tags. North American Journal of Fisheries Management, 35:4, 845–852.

Topping, P.C., and J.H. Anderson. 2018. Green River Juvenile Salmonid Production Evaluation: 2017 Annual Report. Washington Department of Fish and Wildlife. Olympia, WA.